

## PHOTOMETRIC OBSERVATIONS OF TWO TYPE II-P SUPERNOVAE: NORMAL SN II-P 2004A AND UNUSUAL SN 2004ek

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### Abstract

CCD *BVRI* photometry is presented for type II Supernovae 2004A and 2004ek. SN 2004A is found to be a typical SN II-P, with the shape of the light and color curves and maximum luminosity closely matching those for SN 1999em. SN 2004ek shows unusual light curves with long flat plateau in the *B* band, two peaks in the *V* and prominent brightening in the *R* and *I* bands, starting about 45 days past outburst. The brightness decline after the plateau stage is probably quite slow. The plateau luminosity is about 1.5 mag brighter than average for SN II-P.

SN 2004A was discovered by Itagaki on January 9.84 UT at magnitude 15.7 (Nakano and Itagaki, 2004). It is located at  $\alpha = 16^{\text{h}}43^{\text{m}}01^{\text{s}}.90$ ,  $\delta = +36^{\circ}50'12''.5$  (equinox 2000.0), which is approximately  $22''$  west and  $17''$  north from the poorly defined nucleus of Sc galaxy NGC 6207. Kawakita et al. (2004) reported that spectra obtained on January 11 showed blue continuum and prominent H Balmer lines with P Cyg profiles, indicating young SN II. The expansion velocity was estimates as  $12000 \text{ km s}^{-1}$ . The detailed photometric and spectroscopic study of SN 2004A was presented by Hendry et al. (2006), they also reported probable identification of a progenitor star in pre-explosion *HST* images.

SN 2004ek was discovered by Boles, Puckett and Cox (2004) on September 9.97 UT in Sb galaxy UGC 724 at magnitude 17.1. The position of SN is  $\alpha = 1^{\text{h}}09^{\text{m}}58^{\text{s}}.51$ ,  $\delta = +32^{\circ}22'47''.7$  (equinox 2000.0), which is  $11''$  west and  $41''$  north from the center of the galaxy. Modjaz et al. (2004) reported that spectrum obtained on September 14.47 was similar to the early spectra of SN 1993J and showed featureless blue continuum indicating young SN II. Filippenko et al. (2004) confirmed these conclusions with spectroscopic observations carried out on September 24. The spectrum revealed blue continuum with weak hydrogen Balmer and Fe II absorption lines, although the weak  $\text{H}\alpha$  line was almost entirely in emission.

We carried out observations of SN 2004A and 2004ek with the following telescopes and CCD cameras: 60-cm reflector of Crimean Observatory of Sternberg Astronomical Institute (C60) equipped with Roper Scientific VersArray1300B CCD camera (a), or Apogee AP-7p camera (b); 50/70-cm meniscus telescope of Crimean Observatory (C50) with Meade Pictor 416XT camera; 70-cm reflector in Moscow (M70) with Apogee AP-47p (a) or AP-7p (b) cameras. On January 30 images of SN 2004A were obtained with 50-cm reflector at Tatranska Lomnica in Slovakia equipped with SBIG ST-10 camera (S50).

The color terms for C60 and M70 were reported by Tsvetkov et al. (2006). The observations at C50 were carried out only with *V* filter which was close to standard system, and no correction was applied. The *UBVRI* passbands at S50 were quite close to standard, and only minor corrections were needed.

The standard image reductions and photometry were made using IRAF.<sup>†</sup> Photometric measurements of SNe were made relative to local standard stars using PSF-fitting with IRAF DAOPHOT package. Both SNe occurred quite far from the centers of their parent galaxies. At the position of SN 2004ek practically no host galaxy background was present, while for SN 2004A it was noticeable on the frames taken with longer exposures, when SN was faint. Subtraction of host galaxy images was applied to some SN 2004A frames, but the results were found practically identical to those obtained without subtraction.

The magnitudes of local standards were calibrated on photometric nights, when photometric standards were observed at different airmasses. They are reported in Table 1, the images of SNe with marked local standards are shown in Figs. 1,2. The results of photometry of supernovae are presented in Tables 2,3.

**SN 2004A.** We started monitoring this SN on 2004 January 30, 21 days after discovery, and continued observations until November 21. The magnitudes for our local standards were derived also by Hendry et al. (2006), and the mean differences between the two data sets are:  $\overline{\Delta B} = 0.13 \pm 0.01$ ;  $\overline{\Delta V} = 0.08 \pm 0.01$ ;  $\overline{\Delta R} = 0.05 \pm 0.02$ ;  $\overline{\Delta I} = 0.05 \pm 0.02$ . The differences of  $B$  and  $V$  magnitudes are quite significant. Hendry et al. (2006) presented also another set of magnitudes, based on data from SDSS DR4. We found that these magnitudes are in much better agreement with our calibration:  $\overline{\Delta B} = -0.02 \pm 0.03$ ;  $\overline{\Delta V} = -0.04 \pm 0.02$ ;  $\overline{\Delta R} = -0.03 \pm 0.03$ ;  $\overline{\Delta I} = 0.04 \pm 0.01$ . However, Hendry et al. (2006) preferred their own calibration for reduction of SN 2004A photometry. We corrected the magnitudes from Hendry et al. (2006) for the differences we found between the calibrations of local standards and plotted them together with our data in Fig. 3. Also shown are the results of CCD photometry (mostly unfiltered) reported at SNWeb.<sup>‡</sup> They show large systematic differences compared to our data, but are tracing the early rising part of the light curve and so are valuable for defining the explosion date.

We fit the light curves of a typical SN II-P 1999em (Leonard et al., 2002; Elmhamdi et al., 2003a; Hamuy et al., 2001) to the data for SN 2004A and find a very good match, which is evident from Fig. 3. The comparison confirms that explosion occurred on 2004 January 6 (JD 2453011), as estimated by Hendry et al. (2006). The plateau stage starts on JD 2453018. The end of plateau can be defined in different ways; if we assume that it is marked by the point on the light curve, corresponding to half of the brightness drop from plateau to the linear tail, which is at about JD 242453124, then the plateau lasted for 106 days. The maximum brightness was reached at about JD 2453075 in all bands except  $B$ :  $V_{max} = 15.5$ ,  $R_{max} = 15.0$ ,  $I_{max} = 14.7$ . The rate of decline in  $B$  at the plateau phase was  $0.013 \text{ mag day}^{-1}$ . The linear fits to the  $V$  and  $R$  magnitudes after JD 2453200 give the following decline rates:  $0.0099 \pm 0.0009 \text{ mag day}^{-1}$  in the  $V$  and  $0.0088 \pm 0.0004 \text{ mag day}^{-1}$  in the  $R$  band. These rates are very close to the decay slope of  $^{56}\text{Co}$ , which is  $0.0098 \text{ mag day}^{-1}$ .

The color curves for SN 2004A are presented in Fig. 4 and are compared to the color curves of SN 1999em. The agreement is quite good, except some difference of  $(B - V)$  curves at JD 2453080-120. We have also obtained one estimate of  $U$  magnitude, which is not included into Table 2: on JD 2453034.70  $U = 16.29 \pm 0.08$ , corresponding to the color  $(U - B) = 0.14 \pm 0.09$ . This value is about 0.4 mag bluer than the color of SN 1999em at comparable epoch. Still we conclude that the color evolution of the two SNe is similar and the extinction for them is also quite close. The Galactic extinction in the direction of NGC 6207 is small:  $A_V = 0.05$  according to Schlegel et al. (1998). For SN 1999em total extinction of  $A_V \approx 0.3$  is accepted in most of the works (Elmhamdi et al., 2003a). We

<sup>†</sup>IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA under cooperative agreement with the National Science Foundation

<sup>‡</sup>[http://www.astrosurf.com/snweb2/2004/04A\\_/04A\\_Meas.htm](http://www.astrosurf.com/snweb2/2004/04A_/04A_Meas.htm)

conclude that for SN 2004A the total extinction is close to this value.

The distance to NGC 6207 is rather controversial: the radial velocity corrected for the Virgo infall is  $1240 \text{ km s}^{-1}$  according to NASA/IPAC Extragalactic Database<sup>†</sup> (NED), corresponding to distance of 17 Mpc with  $H_0=73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . However, Hendry et al. (2006) estimate the distance using *HST* photometry of the brightest supergiants and find out that this method gives distances in the range from 17.7 to 26.8 Mpc. Finally they accept the mean of different estimates, including kinematic, which is  $20.3 \pm 3.4 \text{ Mpc}$ . Recently the distance to NGC 6207 was also estimated by *I*-band Tully-Fisher relation (Springob et al., 2007) and was found to correspond to radial velocity  $1346 \text{ km s}^{-1}$ . This means the distance of 18.4 Mpc, and we accept this value as more probable. Using this distance and extinction  $A_V = 0.3$  we construct the absolute *V* light curve, which is illustrated in Fig. 7. The light curve of SN 1999em is plotted for comparison (with Cepheid distance 11.7 Mpc and  $A_V = 0.3$ ). Both SNe appear quite similar, although SN 1999em is about 0.5 mag brighter at the plateau stage. With absolute magnitude at plateau of  $M_V = -16.1$  SN 2004A certainly belongs to SN II-P with normal luminosity.

We can try to estimate also the amount of  $^{56}\text{Ni}$  ejected in the explosion by three methods: comparison with the tail luminosity of SN 1987A; correlations between  $^{56}\text{Ni}$  mass and plateau  $M_V$  and the steepness parameter  $S$ , which is the maximum gradient during the transition from plateau to the tail, in  $\text{mag day}^{-1}$  (Elmhamdi et al., 2003b). According to our data, the luminosity at radioactive tail for SN 2004A is about 0.8 mag less than for SN 1987A, and assuming that the same relation holds for bolometric luminosity, we derive  $^{56}\text{Ni}$  mass in SN 2004A to be about 2.07 times less than in SN 1987A, that is  $0.036 M_\odot$ . We estimate the parameter  $S$  for SN 2004A to be approximately  $0.12 \text{ mag day}^{-1}$ , although the coverage of the light curve is not quite good at that stage, this value corresponds to  $M(^{56}\text{Ni}) = 0.027 M_\odot$ . And finally, the correlation between plateau luminosity and  $^{56}\text{Ni}$  mass yields  $M(^{56}\text{Ni}) = 0.039 M_\odot$ . We conclude that all estimates agree reasonably well and confirm that SN 2004A is a normal SN II-P.

**SN 2004ek.** We observed this SN from 2004 September 14 (5 days after discovery) until 2005 February 10. The light curves are presented in Fig. 5, where we also plotted unfiltered CCD magnitudes reported at SNWeb.<sup>†</sup> These data show the early rise of brightness and allow to conclude that the explosion likely occurred at about September 8 (JD 2453256). SN 2004ek certainly belongs to the class of SN II-P, but the differences between the light curves of SN 2004ek and those for typical SNe II-P is evident. In the *B* band SN 2004ek has a long period (JD 2453290-340) of constant brightness, while all normal SNe II-P have nearly linear decline at that stage. In the *V* there are two peaks on the light curve, one immediately after outburst and the second at about JD 2453330. In the *R* and *I* bands after the period of constant brightness there is a prominent increase of luminosity, amounting to 0.3 mag in *R* and 0.4 mag in *I*. The early decline after the plateau is probably quite slow, the gradient in *R* is only  $0.013 \text{ mag day}^{-1}$ . These features are unique among well-studied SN II-P.

The color curves are illustrated in Fig. 6 and are compared to the curves for SN 1999em. The  $(B - V)$  curves of SN 2004A and 1999em are different, although the values of  $(B - V)$  at early stage are similar. The shape of  $(V - R)$  and  $(R - I)$  curves is similar for both objects.

As SN 2004ek exploded far from the center of its parent galaxy, at the distance close to the photometric radius, the extinction inside the galaxy should be small. The Galactic extinction in the direction of UGC 724 is  $A_V = 0.22$  according to Schlegel et al. (1998).

<sup>†</sup><http://nedwww.ipac.caltech.edu>

<sup>†</sup>[http://www.astrosurf.com/snweb2/2004/04ek\\_/04ek\\_Meas.htm](http://www.astrosurf.com/snweb2/2004/04ek_/04ek_Meas.htm)

Accepting this value as total extinction and the distance 73 Mpc from NED, we obtain maximum absolute magnitude  $M_V = -17.95$ , a high luminosity for SN II-P. The absolute  $V$ -light curve for SN 2004ek is shown in Fig. 7. SN 2004ek is similar in luminosity to one of the brightest known SN II-P 1992am (Schmidt et al., 1994), but the shape of the light curve is different. The light curves of SNe 1999em and 2004ek can also be compared on Fig. 7, and it is evident that the plateau lasted longer for SN 2004ek and that the shape of the light curve on the plateau is different.

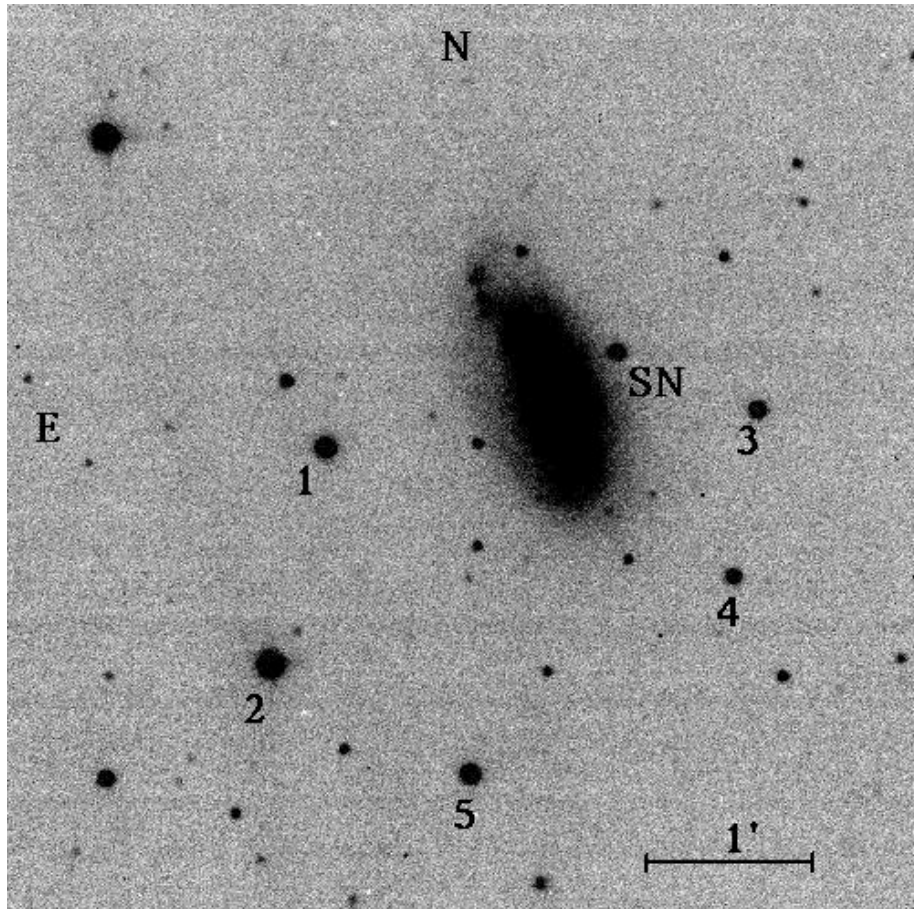
The reports on spectroscopic observations of SN 2004ek (Modjaz et al., 2004; Filippenko et al., 2004) confirm the peculiar nature of this object. Spectrum obtained on September 14.47 (about 6 days past explosion) showed featureless blue continuum, and even on September 24 (16 days past outburst) the absorption lines were weak, and  $H\alpha$  line was almost entirely in emission. The spectra of typical SNe II-P already show prominent hydrogen Balmer lines with P-Cyg profiles at phase about 2-3 days, and at phase  $\sim 16$  days the absorption lines become much deeper.

SN 2004ek has peculiar shape of the light curves in  $BVRI$  bands and shape of  $(B - V)$  color curve, long duration of the plateau and high luminosity, unusual spectral evolution. Among well-studied SNe II-P there is no analog to SN 2004ek. Unfortunately, our observations of this object are not detailed, and we have no data on the tail of the light curve. We appeal to all observers who collected data on this SN to turn their attention to this interesting object, which may be important for revealing the diversity of type II SNe.

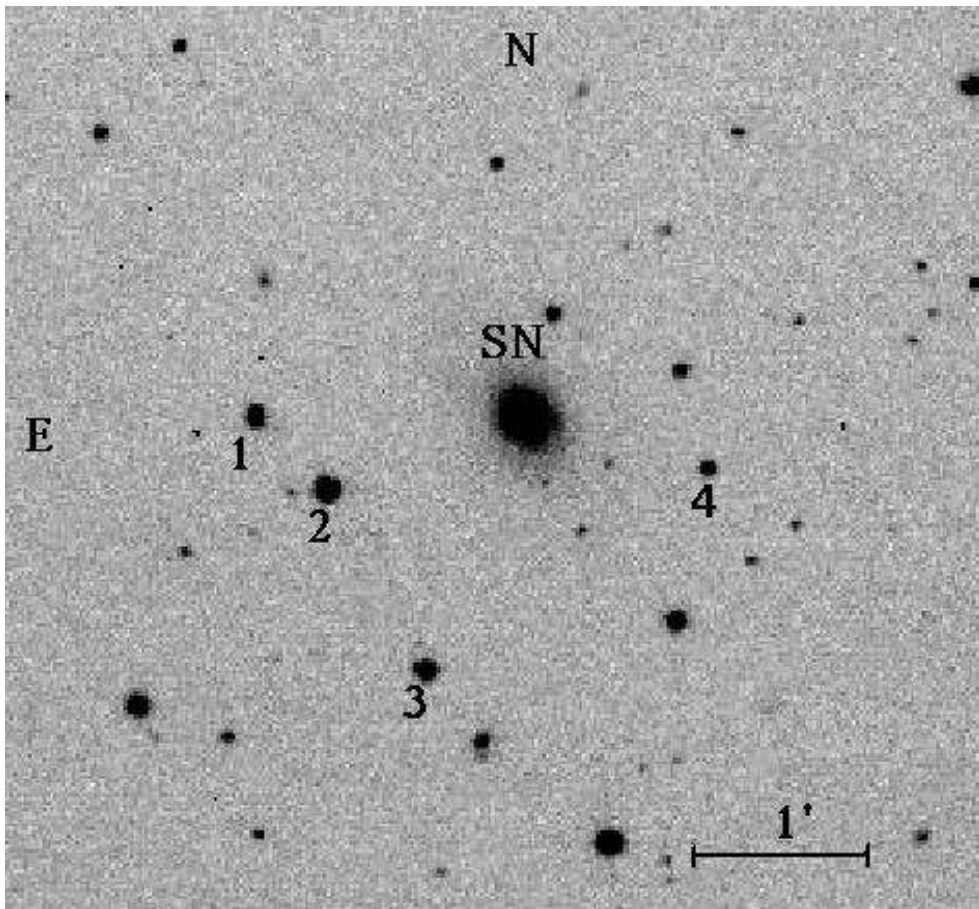
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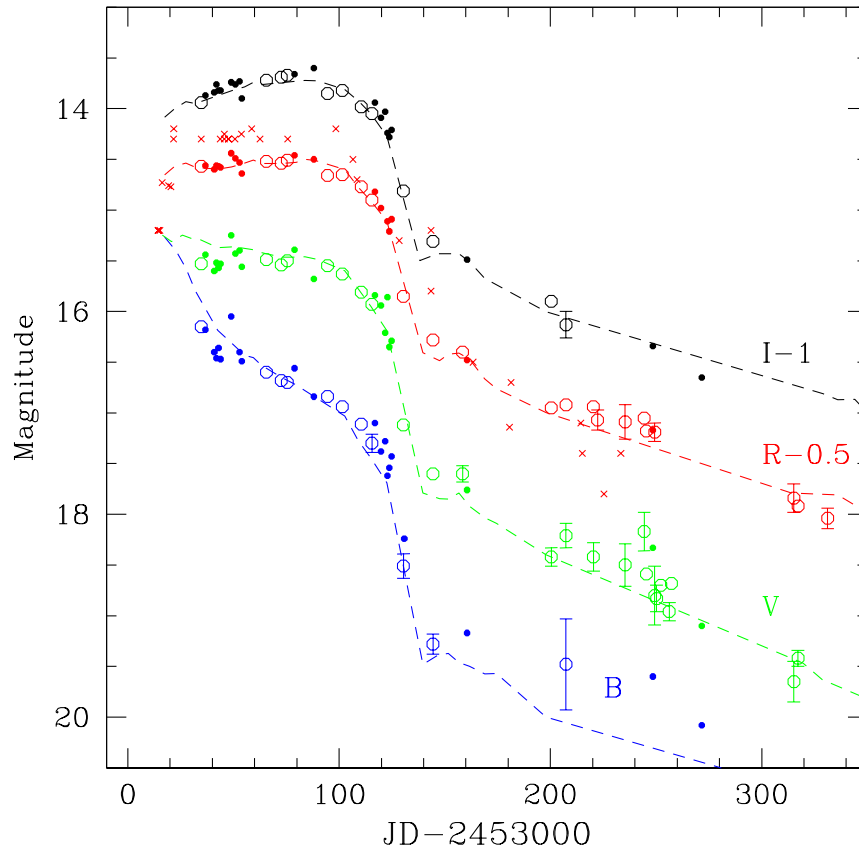
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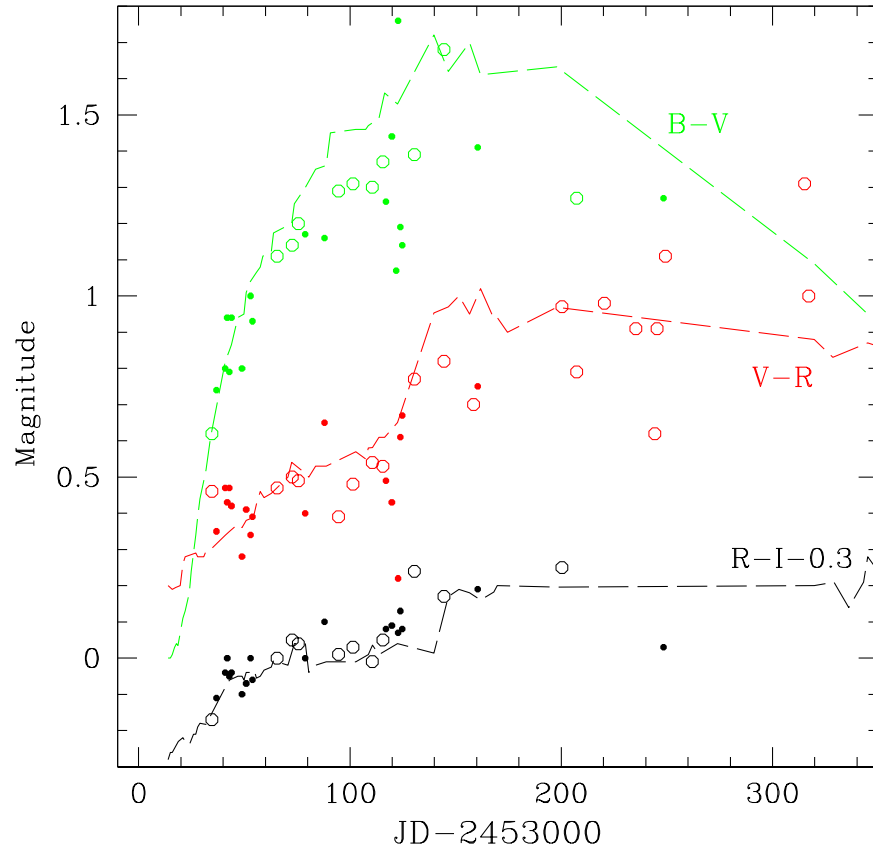
**Figure 1.** SN 2004A in NGC 6207 with local standard stars



**Figure 2.** SN 2004ek in UGC 724 with local standard stars

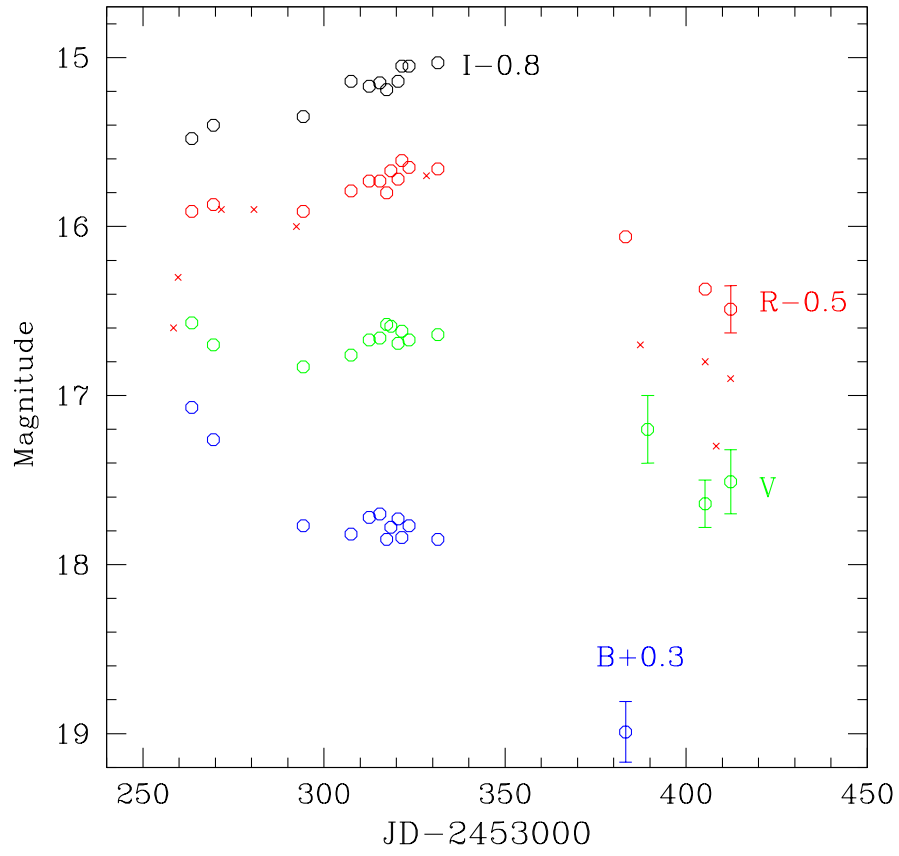


**Figure 3.** *BVRI* light curves of SN 2004A, showing our photometry (circles), that of Hendry et al. (2001) (dots) and the magnitudes reported at SNWeb (crosses). Error bars for our magnitudes are plotted only when they exceed the size of a point. The dashed lines are the light curves of SN 1999em

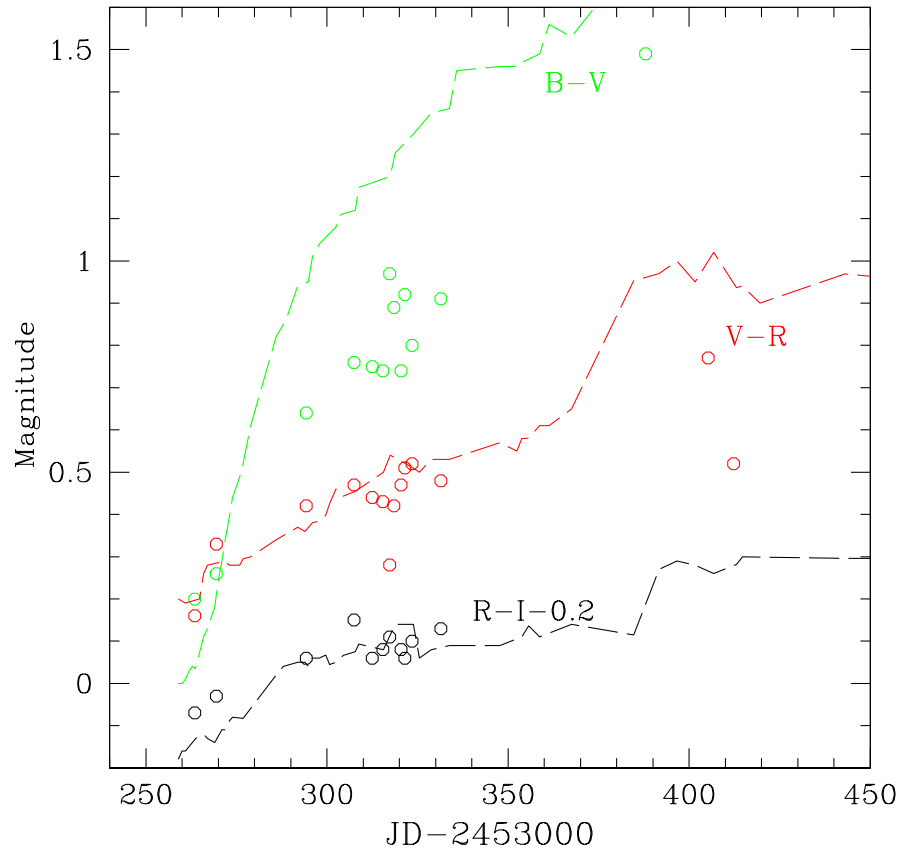


**Figure 4.** The color curves of SN 2004A, showing our photometry (circles) and that of Hendry et al. (2001) (dots). The dashed lines are the color curves of SN 1999em

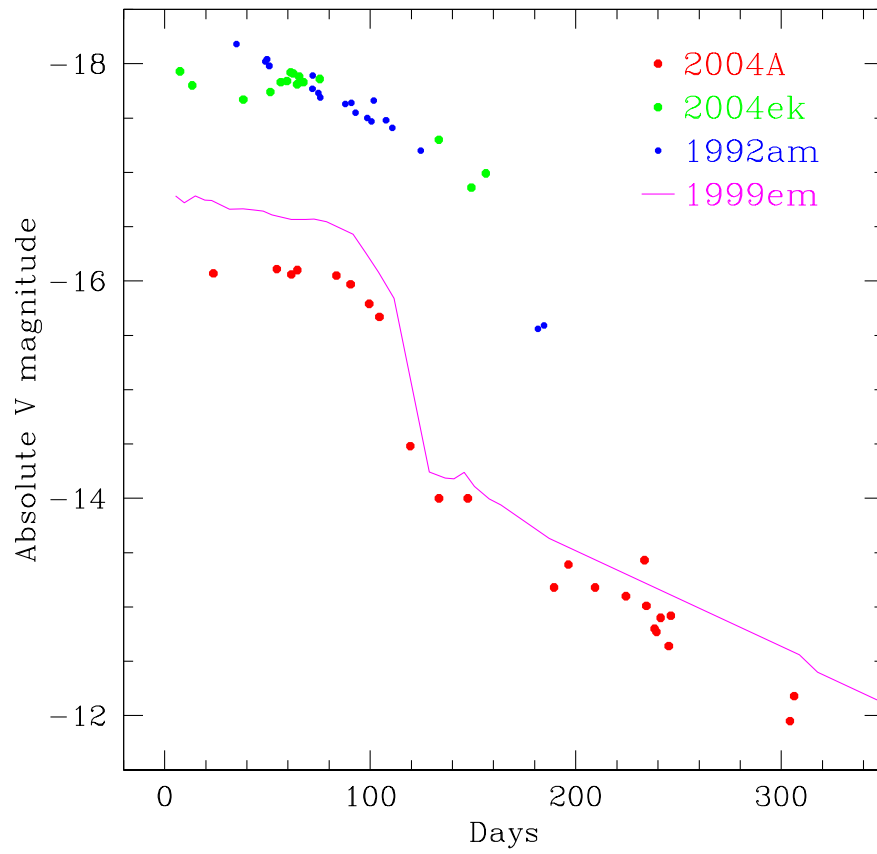




**Figure 5.** *BVRI* light curves of SN 2004ek. Circles show our data, crosses are for observations reported at SNWeb. Error bars for our magnitudes are plotted only when they exceed the size of a point



**Figure 6.** The color curves of SN 2004ek. The dashed lines are the color curves of SN 1999em



**Figure 7.** The absolute  $V$  light curves of SNe 2004A and 2004ek compared to those for SNe 1999em and 1992am

Table 1: Magnitudes of local standard stars

Star	$U$	$\sigma_U$	$B$	$\sigma_B$	$V$	$\sigma_V$	$R$	$\sigma_R$	$I$	$\sigma_I$
2004A-1	14.70	0.07	14.66	0.04	14.05	0.01	13.65	0.03	13.38	0.03
2004A-2	14.55	0.06	14.00	0.03	13.11	0.02	12.55	0.03	12.15	0.04
2004A-3			16.12	0.03	15.22	0.01	14.78	0.02	14.40	0.04
2004A-4			16.39	0.03	15.66	0.02	15.27	0.03	14.94	0.05
2004A-5			15.05	0.04	14.34	0.02	13.96	0.03	13.61	0.05
2004ek-1			15.59	0.01	14.96	0.01	14.58	0.01	14.28	0.01
2004ek-2			14.97	0.01	14.01	0.01	13.46	0.01	12.97	0.02
2004ek-3			15.31	0.01	14.66	0.01	14.29	0.02	13.96	0.02
2004ek-4			17.05	0.04	16.50	0.02	16.21	0.03	15.90	0.05

Table 2: Observations of SN 2004A

JD 2453000+	$B$	$\sigma_B$	$V$	$\sigma_V$	$R$	$\sigma_R$	$I$	$\sigma_I$	Tel.
34.70	16.15	0.03	15.53	0.04	15.07	0.02	14.94	0.03	S50
65.53	16.60	0.02	15.49	0.02	15.02	0.02	14.72	0.02	C60b
72.62	16.68	0.04	15.54	0.02	15.04	0.02	14.69	0.03	C60b
75.56	16.70	0.03	15.50	0.02	15.01	0.02	14.67	0.03	M70a
94.54	16.84	0.07	15.55	0.03	15.16	0.05	14.85	0.06	M70a
101.48	16.94	0.03	15.63	0.02	15.15	0.01	14.82	0.02	M70a
110.51	17.11	0.03	15.81	0.02	15.27	0.03	14.98	0.02	M70a
115.52	17.30	0.09	15.93	0.03	15.40	0.03	15.05	0.04	M70a
130.49	18.51	0.12	17.12	0.07	16.35	0.03	15.81	0.06	M70a
144.44	19.28	0.10	17.60	0.06	16.78	0.02	16.31	0.04	M70a
158.43			17.60	0.08	16.90	0.03			M70a
200.40			18.42	0.09	17.45	0.05	16.90	0.07	M70b
207.40	19.48	0.45	18.21	0.12	17.42	0.04	17.13	0.13	M70b
220.39			18.42	0.14	17.44	0.06			M70b
222.38					17.57	0.10			M70b
235.38			18.50	0.21	17.59	0.17			M70b
244.38			18.17	0.19	17.55	0.06			M70b
245.37			18.59	0.06	17.68	0.03			C60a
249.33			18.80	0.29	17.69	0.09			M70b
250.26			18.83	0.13					C50
252.25			18.70	0.07					C50
256.26			18.96	0.09					C50
257.23			18.68	0.07					C50
315.21			19.65	0.20	18.34	0.14			C60a
317.22			19.42	0.08	18.42	0.05			C60a
331.24					18.54	0.10			C60a

Table 3: Observations of SN 2004ek

JD 2453000+	$B$	$\sigma_B$	$V$	$\sigma_V$	$R$	$\sigma_R$	$I$	$\sigma_I$	Tel.
263.47	16.77	0.03	16.57	0.03	16.41	0.02	16.28	0.04	M70b
269.41	16.96	0.03	16.70	0.04	16.37	0.04	16.20	0.05	M70b
294.26	17.47	0.03	16.83	0.03	16.41	0.03	16.15	0.03	M70a
307.41	17.52	0.06	16.76	0.04	16.29	0.03	15.94	0.03	M70a
312.51	17.42	0.04	16.67	0.03	16.23	0.03	15.97	0.03	M70a
315.45	17.40	0.04	16.66	0.02	16.23	0.02	15.95	0.05	C60a
317.30	17.55	0.03	16.58	0.02	16.30	0.02	15.99	0.05	C60a
318.50	17.48	0.04	16.59	0.03	16.17	0.04			C60a
320.45	17.43	0.02	16.69	0.02	16.22	0.02	15.94	0.04	C60a
321.47	17.54	0.03	16.62	0.02	16.11	0.01	15.85	0.04	C60a
323.49	17.47	0.03	16.67	0.02	16.15	0.02	15.85	0.03	C60a
331.47	17.55	0.04	16.64	0.02	16.16	0.02	15.83	0.03	C60a
383.27	18.69	0.18			16.56	0.04			M70a
389.37			17.20	0.20					M70a
405.22			17.64	0.14	16.87	0.07			M70a
412.26			17.51	0.19	16.99	0.14			M70a